2012 Feb 13, GCOEシンポジウム「階層の連結」, Kyoto University

Rotating FFLO Superfluid in cold atom gases

Niigata University, Youichi Yanase
Tomohiro Yoshida

Group member (from 2009 Oct.)

Tomohiro Yoshida

Daisuke Maruyama

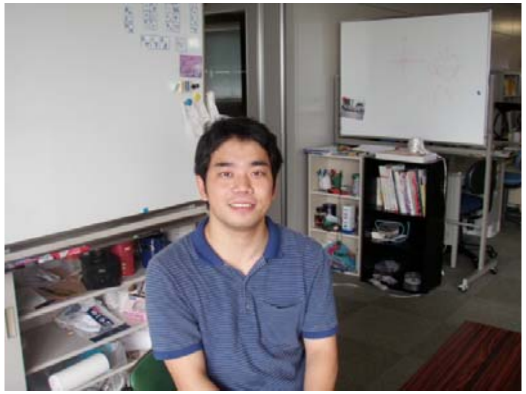
"Non-centrosymmetric Superconductivity"

"FFLO Superfluid"

"Spin triplet Superconductivity"

Sr_2RuO_4

Shuhei Takamatsu



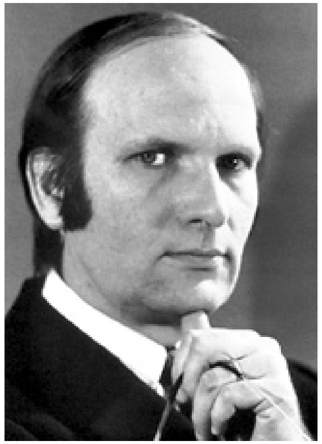
Shunsuke Kawabe

Introduction to FFLO state

Standard theory of Superfluidity/SC


J. Bardeen


L. N. Cooper


J. R. Schrieffer

BCS Theory (1957)

Fermions + Attractive interaction

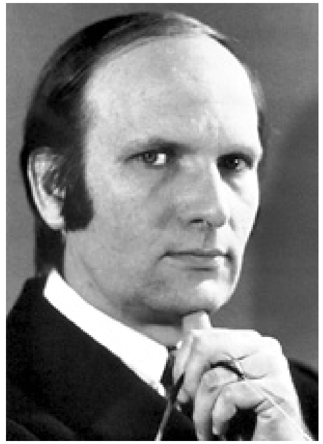
→ Cooper pairs with q=0

Basic Assumption: Total momentum of Cooper pair is zero.

Standard theory of Superfluidity/SC

J. Bardeen

L. N. Cooper



J. R. Schrieffer

BCS Theory (1957)

Fermions + Attractive interaction

→ Cooper pairs with q=0

FFLO state Condensate of Cooper pairs with q≠0

Theory: Fulde-Ferrell (1964), Larkin-Ovchinnikov (1964)

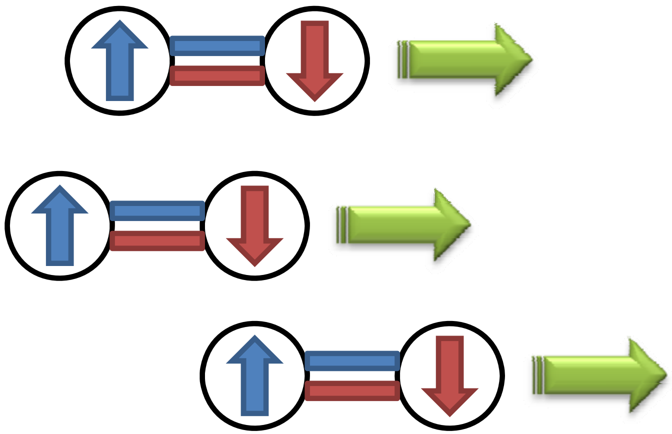
FFLO Superfluidity/Superconductivity

Condesate of Cooper pairs with finite total momentum $\pm q$

→ Multi-component superconductor

Fulde-Ferrell state

$\Delta(r) = \Delta \exp(iqx)$

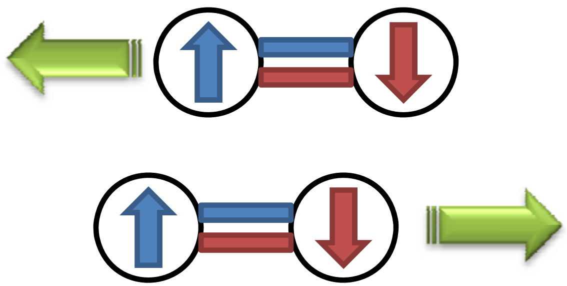


Under current, Non-centro. SC

Broken inversion symmetry

Larkin-Ovchinnikov state

$\Delta(r) = \Delta \cos(qx)$



^{3}He thin film, Superconductor

Broken translation symmetry

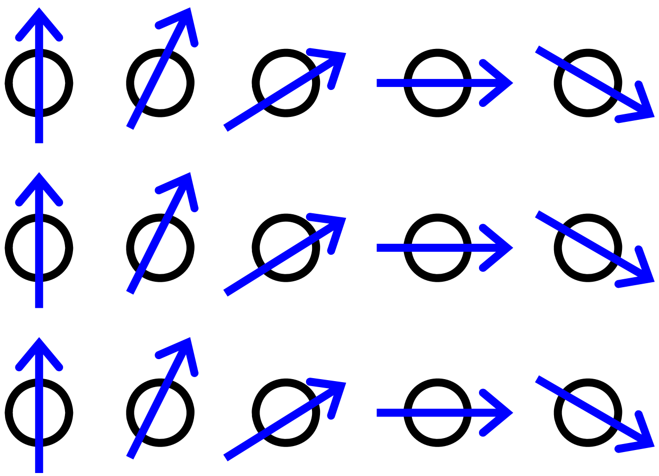
FFLO Superfluidity/Superconductivity

Condesate of Cooper pairs with finite total momentum $\pm q$

→ Multi-component superconductor

Fulde-Ferrell state

$\Delta(r)= \Delta\exp(iqx)$

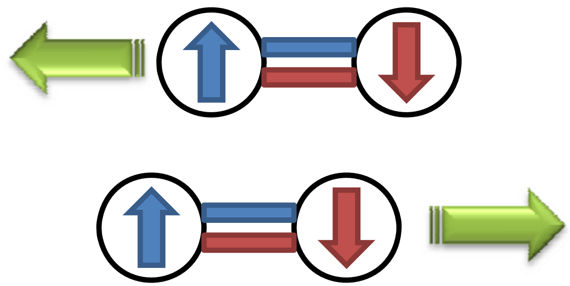


Under current, Non-centro. SC

Broken inversion symmetry

Larkin-Ovchinnikov state

$\Delta(r)= \Delta\cos(qx)$



^{3}He thin film, Superconductor

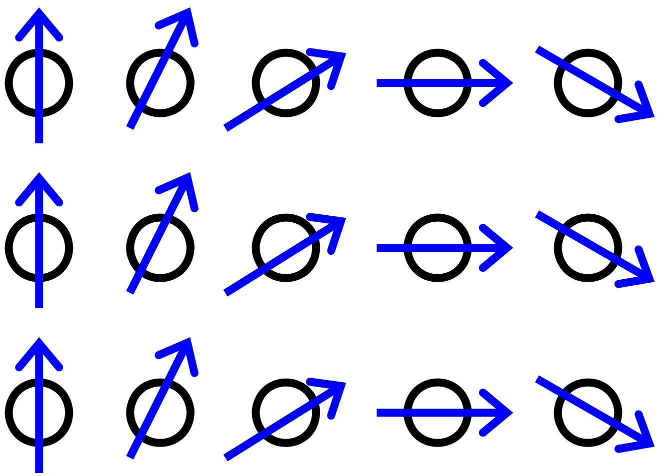
Broken translation symmetry

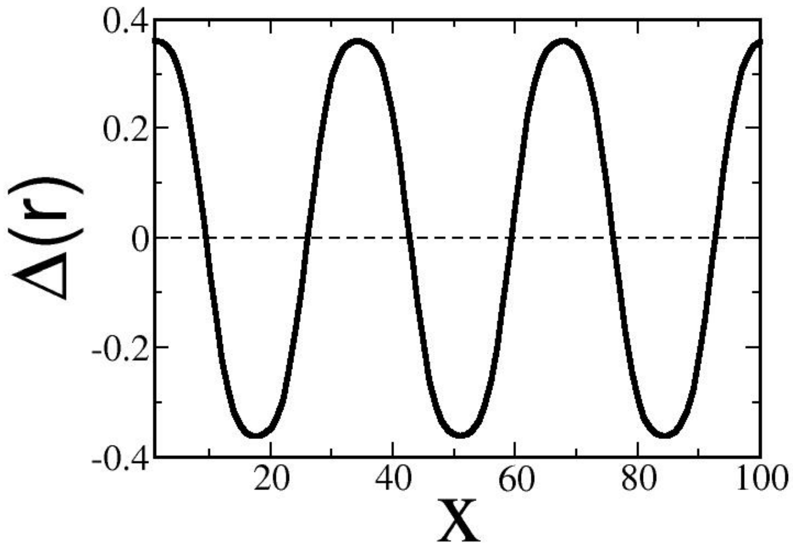
FFLO Superfluidity/Superconductivity

Condesate of Cooper pairs with finite total momentum $\pm q$

→ Multi-component superconductor

Fulde-Ferrell state	Larkin-Ovchinnikov state
$\Delta(r) = \Delta \exp(iqx)$	$\Delta(r) = \Delta \cos(qx)$





Under current, Non-centro. SC

Broken inversion symmetry

^{3}He thin film, Superconductor

Broken translation symmetry

FFLO Superfluidity/Superconductivity

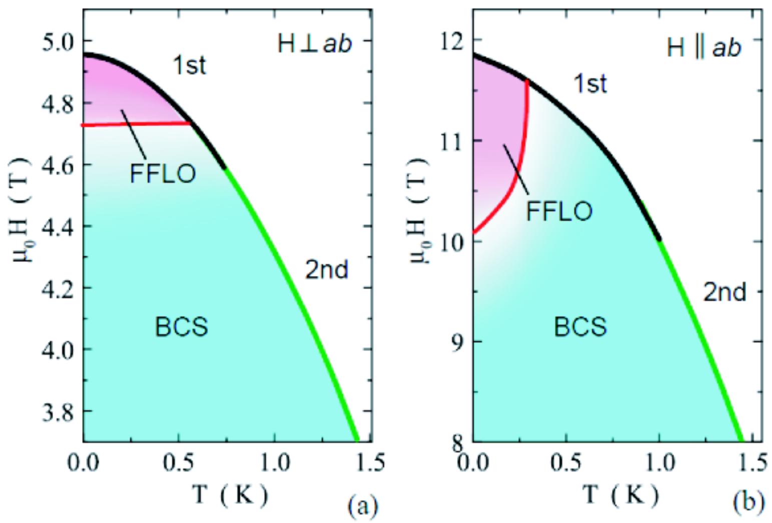
Condesate of Cooper pairs with finite total momentum $\pm q$

Theory: Fulde-Ferrell (1964), Larkin-Ovchinnikov (1964)

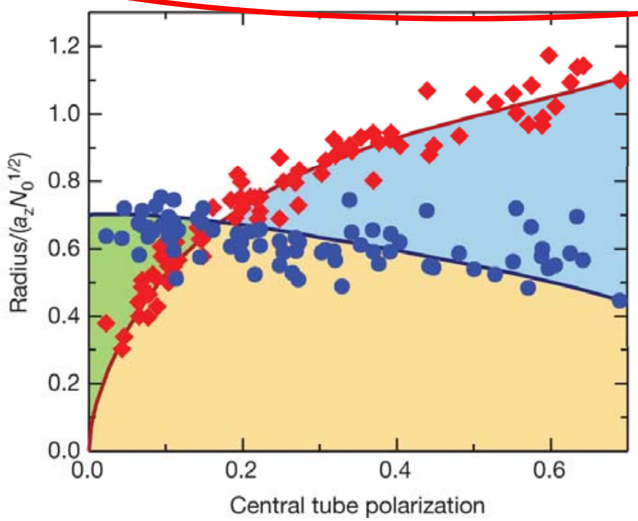
Candidates

(1) Superconductors in magnetic field

$CeCoIn_5$, $(TMTSF)_2X$ .....



(2) Imbalanced cold Fermi gases



MIT, Rice, Paris (2006-)

(3) High density quark matter
(Color superconductivity)

(4) ^{3}He thin film

(5) Stripe phase in Cuprates

Why we couldn't realize FFLO phase in SC for 40 years ?

FFLO phase is suppressed by

(1) Disorder → We need a high quality single crystal

(2) Orbital pair-breaking effect → Low dimension,
Heavy effective mass

Strongly correlated electron systems

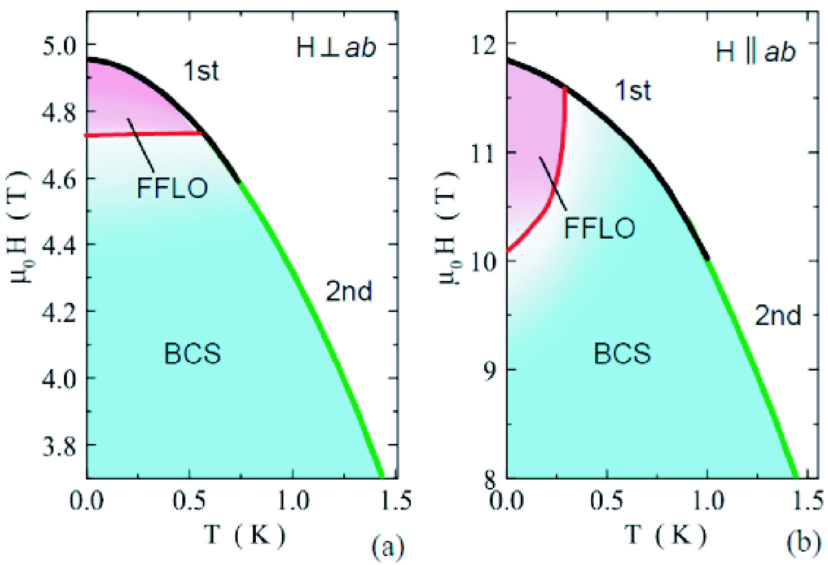
(3) Fermi liquid correction ($F_0^a < 0$)

→ Strongly correlated electron systems ???

Why we could find the FFLO phase ?

Yanase (2008)

(1) $CeCoIn_5$



Matsuda-Shimahara (2007)
Radovan et al. (2003)
Bianchi et al. (2003)

(2) $(TMTSF)_2X$ Yonezawa et al. (2008)

(3) λ-$(BETS)_2X$ Uji et al. (2006)

(4) κ-$(ET)_2X$ Lortz et al. (2007)

Clean and Pauli-limited SC

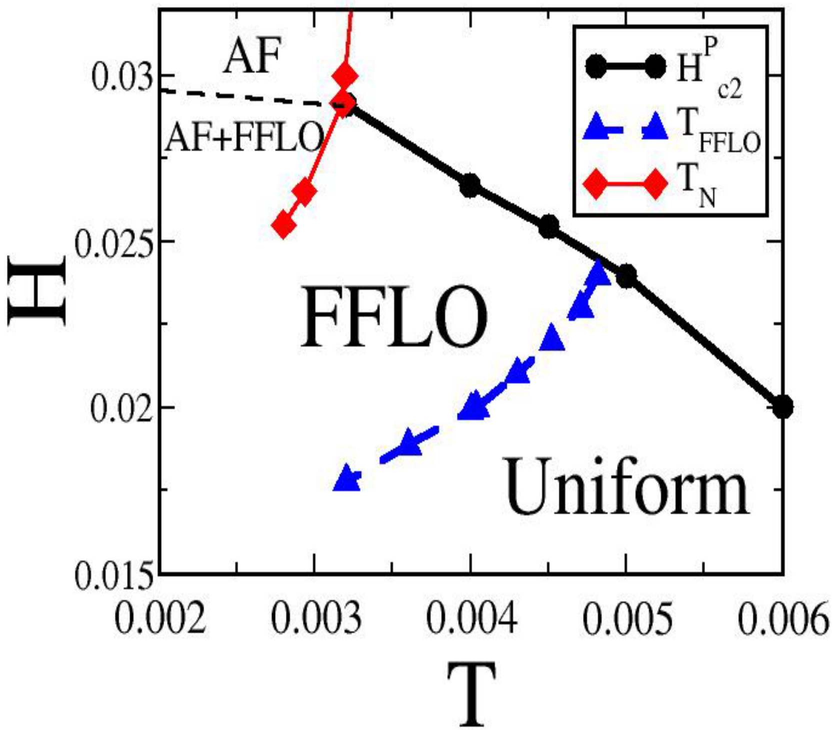
All of these compounds are close to AFQCP

Fermi liquid correction, retardation effect, parity mixing …

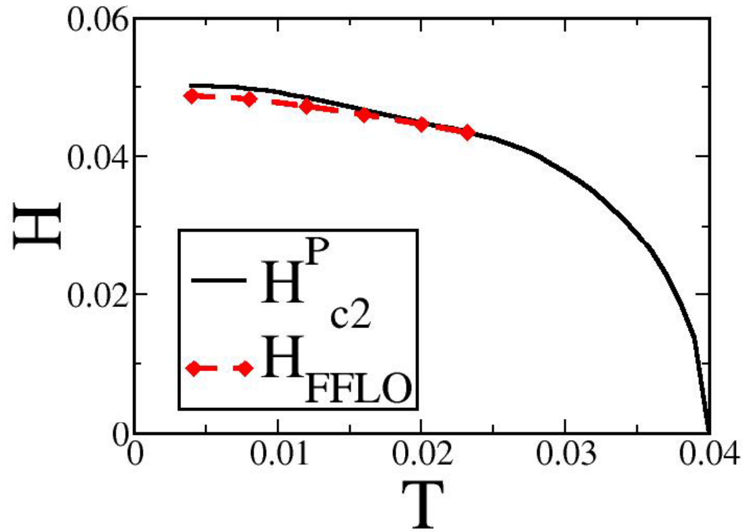
FFLO superconductivity near AFQCP

Yanase (2008)

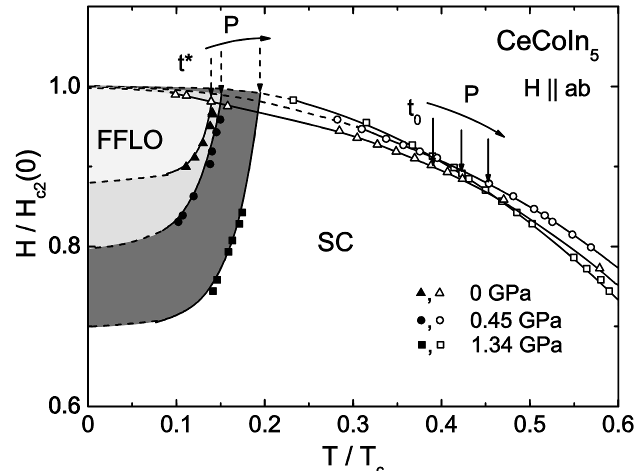
2D Hubbard model + FLEX



BCS theory



$CeCoIn_5$ Miclea et al. (2006)



Antiferromagnetic QCP

Stable FFLO phase

FFLO phase in cold Fermi gases

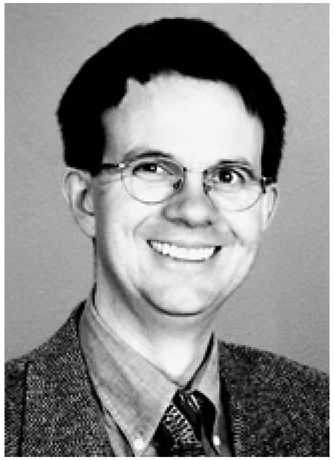
Y. Y. PRB (2009)

T. Yoshida and Y. Y. PRA (2011)

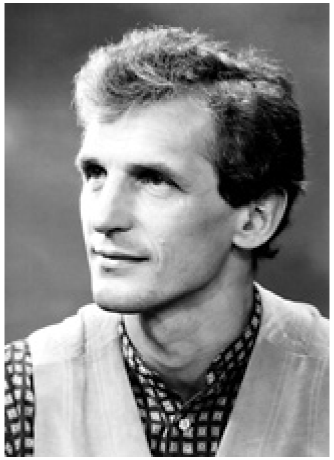
Superfluid in cold atom gases

BEC in dilute Bose gas

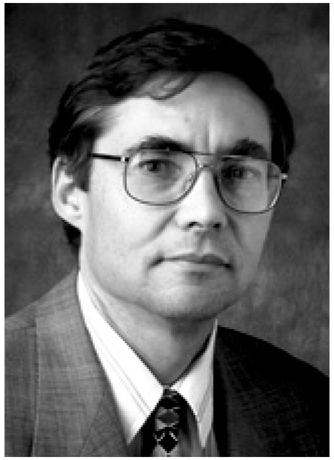
Superfluidity in Fermi gas



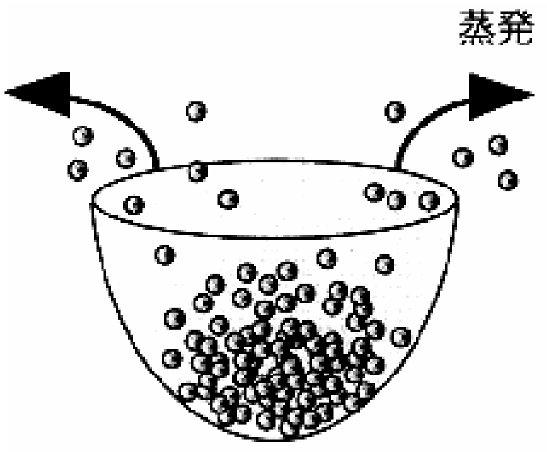
E. A. Cornell



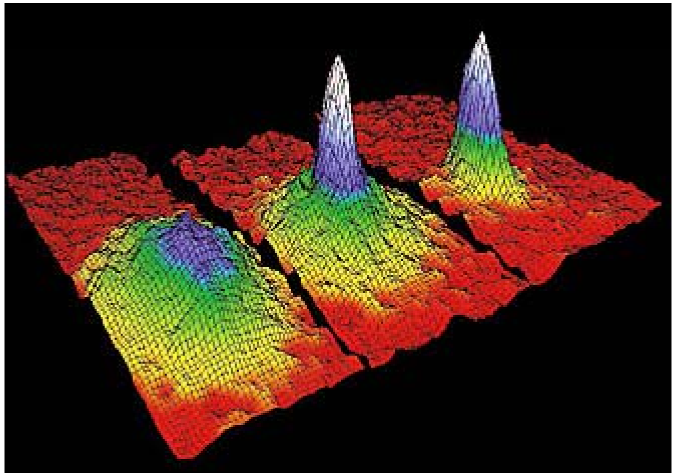
W. Ketterle



C. E. Wieman



Reduced temperature



BEC in ^{87}Rb atoms

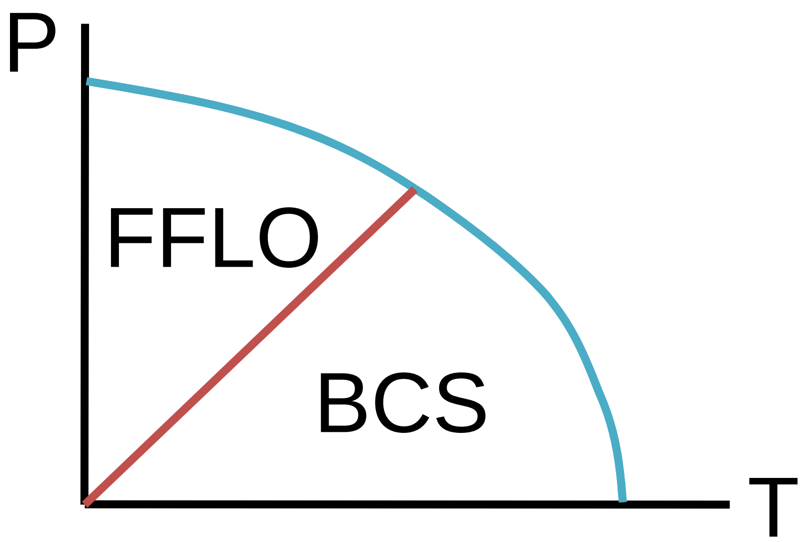
Advantages of cold Fermi gases

(1) Disorder free

(2) No orbital pair-breaking effect → Pure FFLO state without vortex

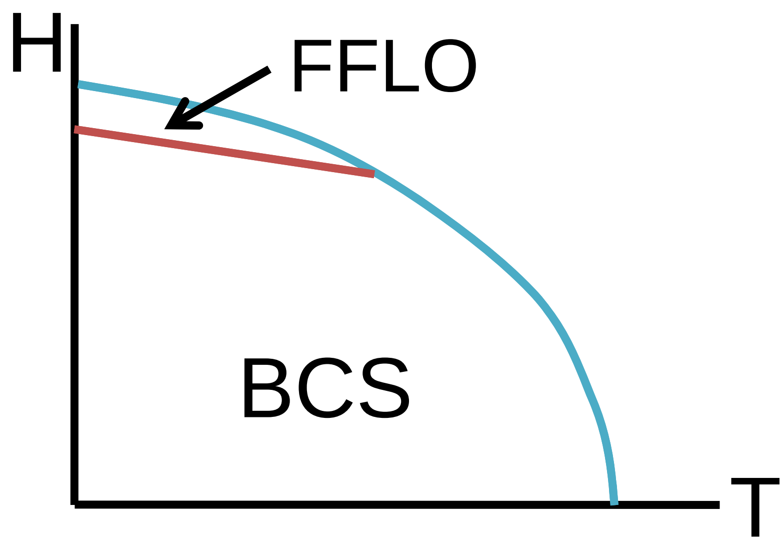
(3) Attractive interaction → Fermi liquid correction stabilizes FFLO

Cold Fermi gases



Discussion with Machida and Mizushima

Superconductors

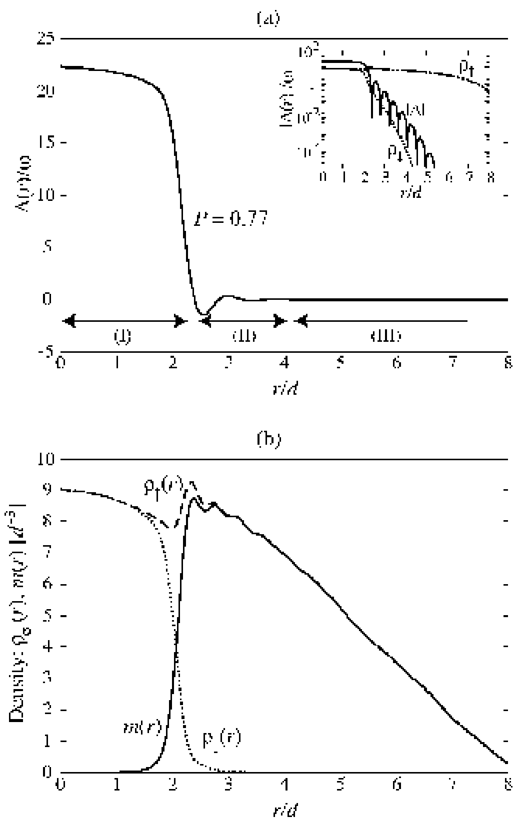


Disadvantage ? : Trap potential

Harmonic trap $W(r) = \frac{1}{2}\omega_{\mathrm{h}}^2 r^2$

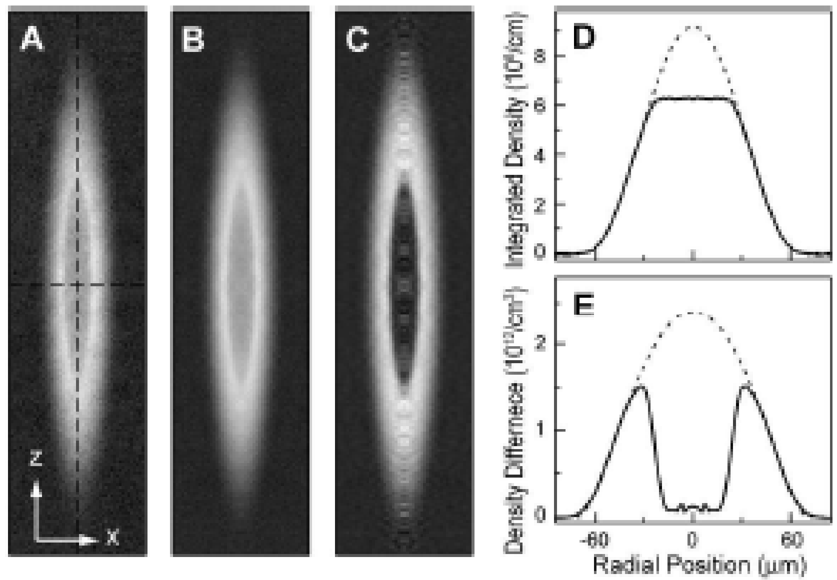
No translation symmetry !!

We cannot distinguish the FFLO state from phase separation



Theory:
Mizushima et al.

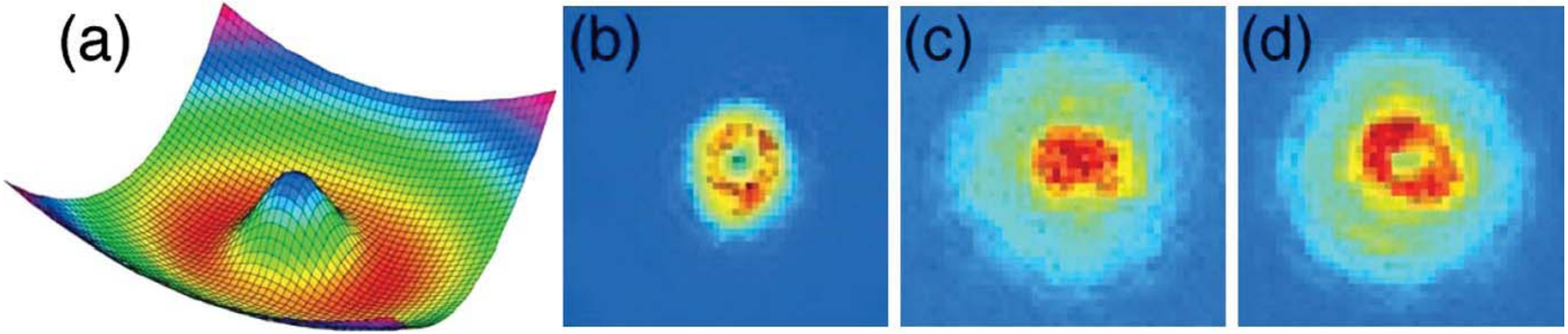
Experiment : Shin et al. (2006)



Toroidal trap

$$W(r) = \frac{1}{2}\omega_{\mathrm{h}}^2 r^2 + \omega_{\mathrm{t}} \exp(-r^2/\xi^2)$$

C. Ryu et al. (2007) in NIST



No translation symmetry
but, rotation symmetry !

Our idea FFLO superfluid phase in the troidal trap

Model

Lattice model in a trap potential

$$H = t \sum_{<i,j>,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + \sum_i (W_i - \mu) n_i - 2H \sum_i S_i^z + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Low density limit → Continuum gas

Trap potential

Harmonic potential $W(r) = \frac{1}{2}\omega_{\rm h}^2 r^2$

Toroidal potential $W(r) = \frac{1}{2}\omega_{\rm h}^2 r^2 + \omega_{\rm t} \exp(-r^2/\xi^2)$

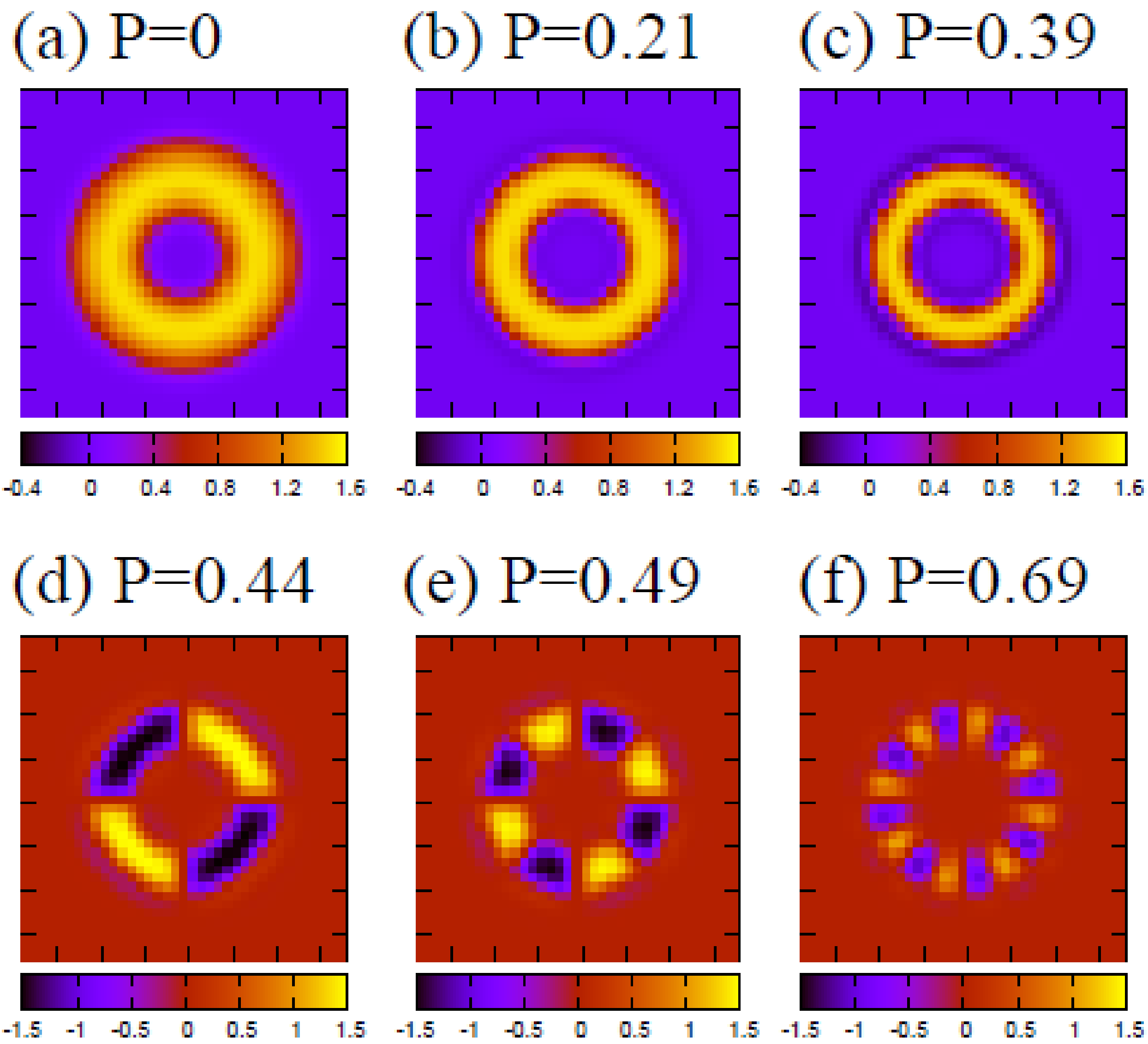
Method

BdG (M.F.A.) , RSTA (Self-consistent 1-loop)

Mean field theory (BdG equation)

Order parameter

Imbalance: $P = (n_1 - n_2)/(n_1 + n_2)$



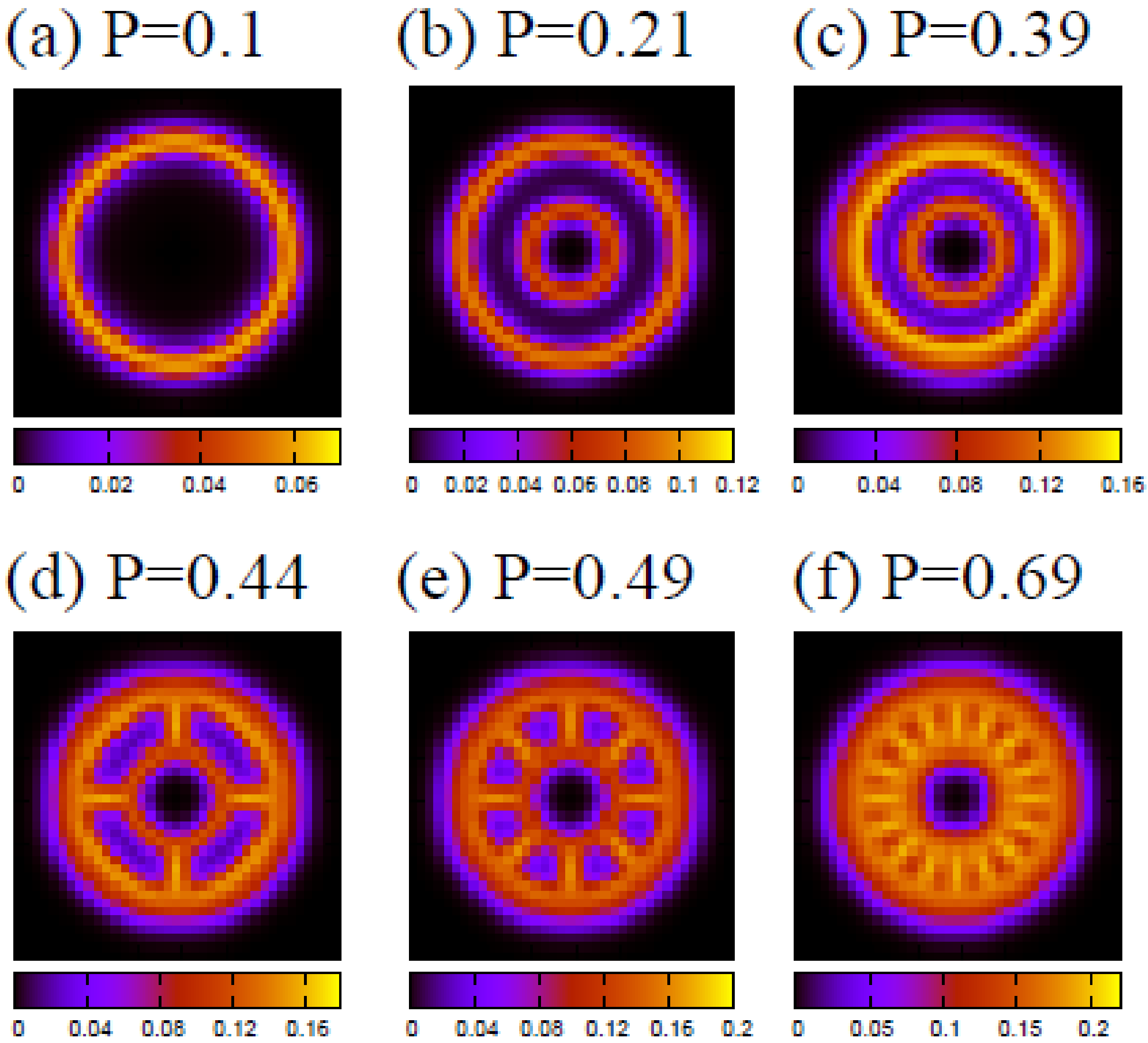
Radial-FFLO

❌ No symmetry breaking

Angular-FFLO

Rotation symmetry breaking !!

Local Population imbalance



Radial-FFLO

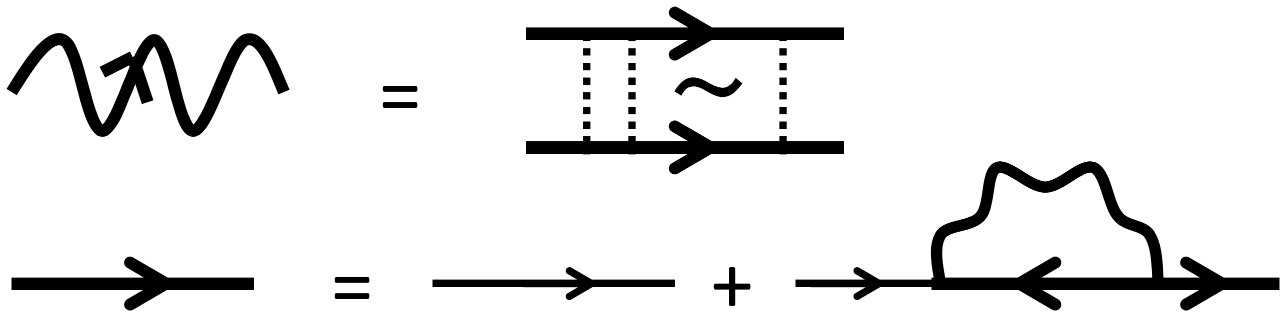
✖ No symmetry breaking

Angular-FFLO

distinguished from phase separation !!

Beyond mean field theory (RSTA)

RSTA= Real Space Self-consistent T-matrix Approximation



Inhomogeneity: Exact → Mesoscopic fluctuation

fluctuation: 1-loop → Thermal fluctuation

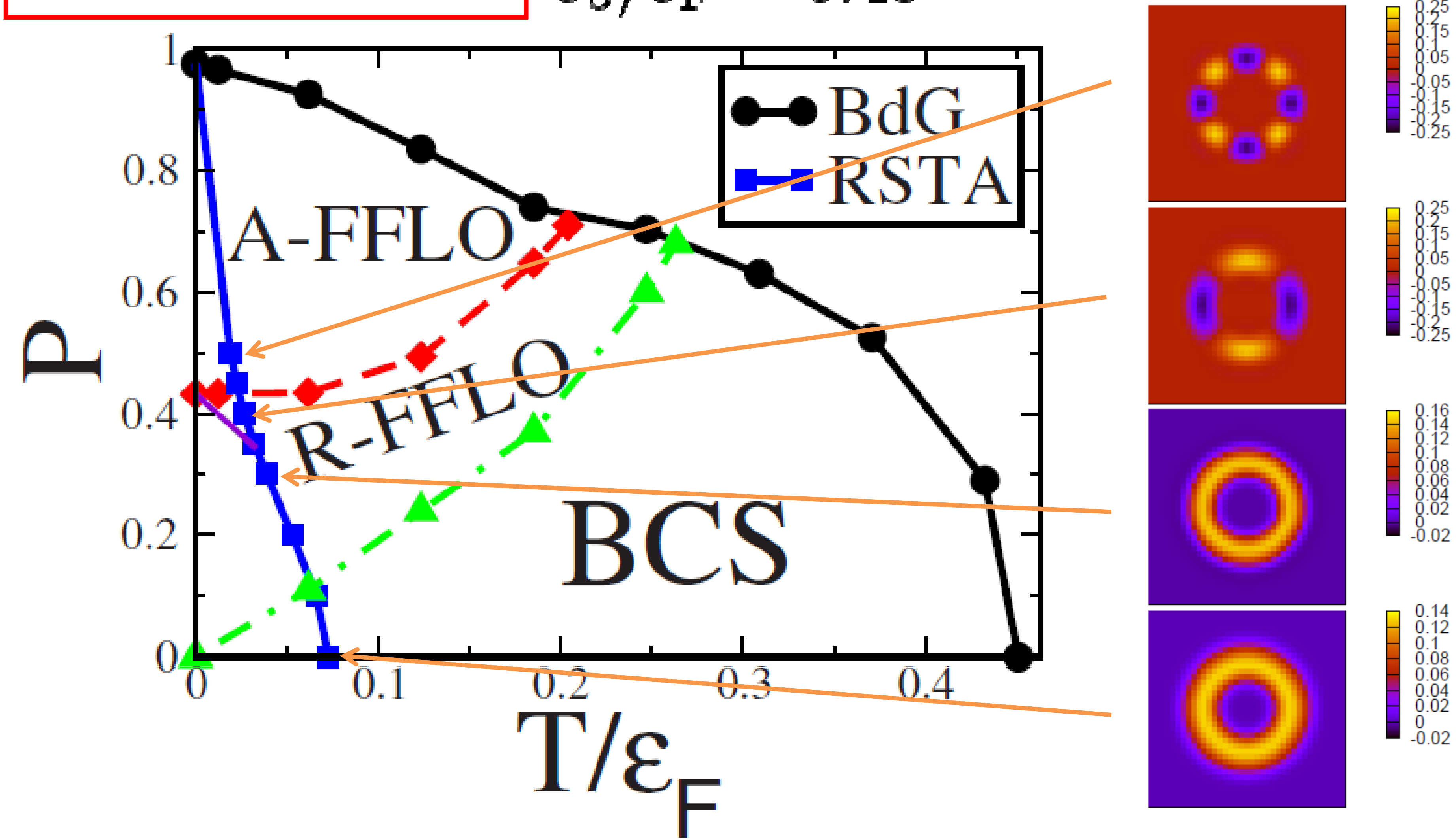
History (1) Pseudogap in disordered high-Tc cuprates (2006)

(2) Superconductor-Insulator transition in Diamond (2008)

Phase diagram in RSTA

BCS side near crossover

$e_b/\varepsilon_F \sim 0.43$



Angular-FFLO state is stable near BCS-BEC crossover !!

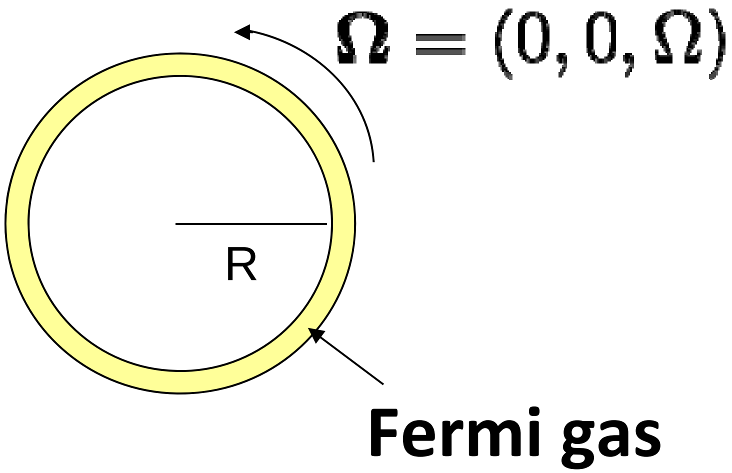
Rotating FFLO phases

T. Yoshida and Y. Y. (2011)

Spontaneous rotation symmetry breaking

→ Intriguing effect of rotation

Rotating FFLO phase in the toroidal trap



Rotation

↓

Phase shift

One dimensional attractive Hubbard model

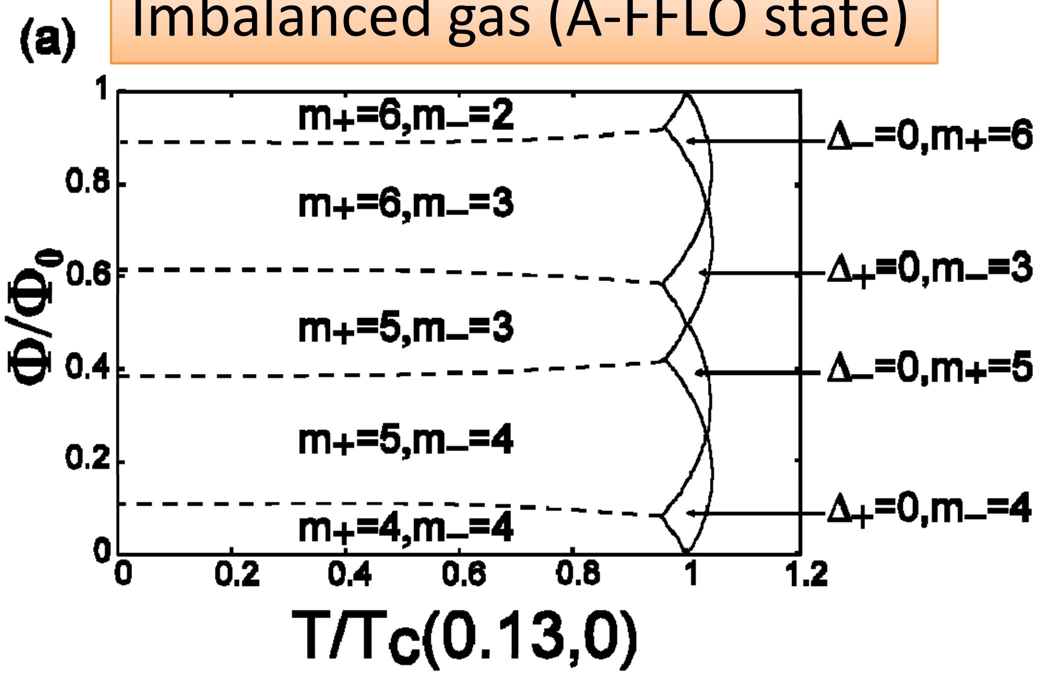
$$H = -t\sum_{i,\sigma}(\mathrm{e}^{i\Phi}\hat{c}^{\dagger}_{i+1\sigma}\hat{c}_{i\sigma} + \mathrm{e}^{-i\Phi}\hat{c}^{\dagger}_{i-1\sigma}\hat{c}_{i\sigma}) - |U|\sum_{i}\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} - \sum_{i,\sigma}\mu_{\sigma}\hat{n}_{i\sigma}$$

$$t = 1/2m, \quad \Phi = R\Omega/2t$$

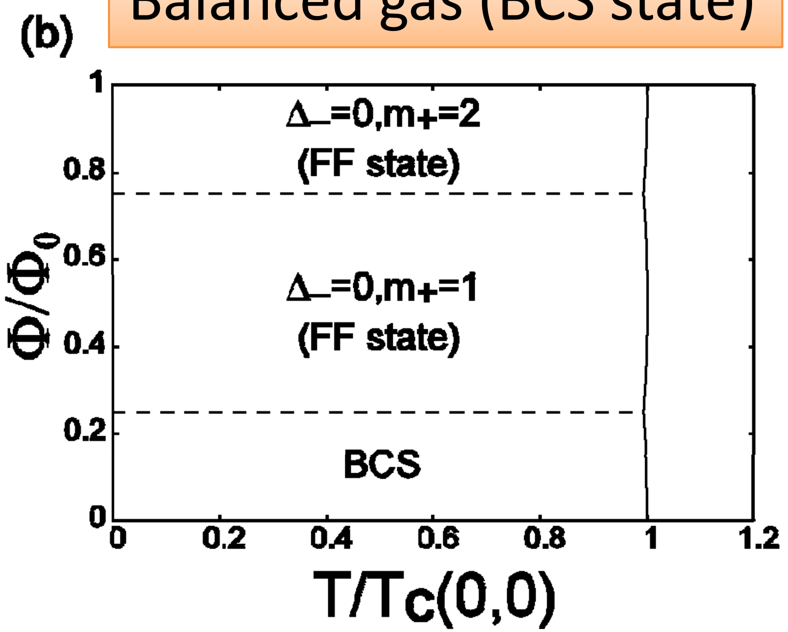
quasi-1D model in BCS region → BdG equation

T-Φ phase diagram

Imbalanced gas (A-FFLO state)

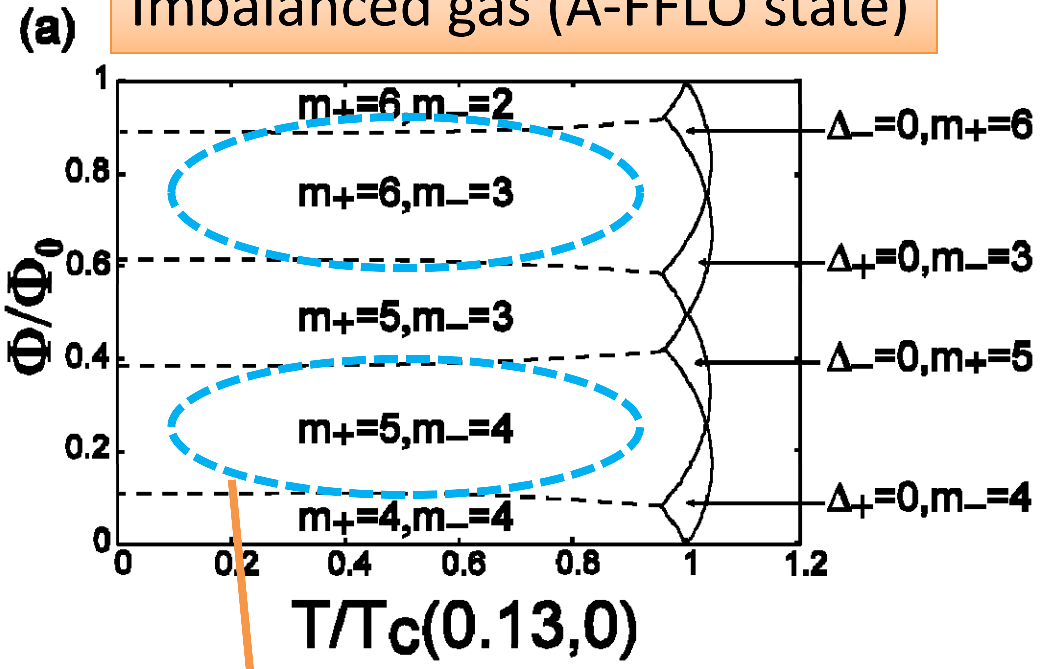


Balanced gas (BCS state)

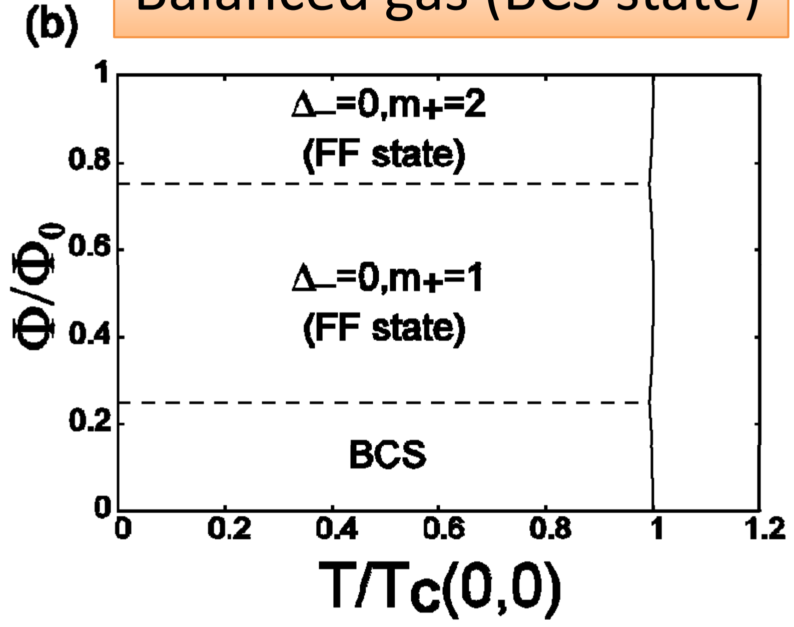


Half quantum vortex state

Imbalanced gas (A-FFLO state)

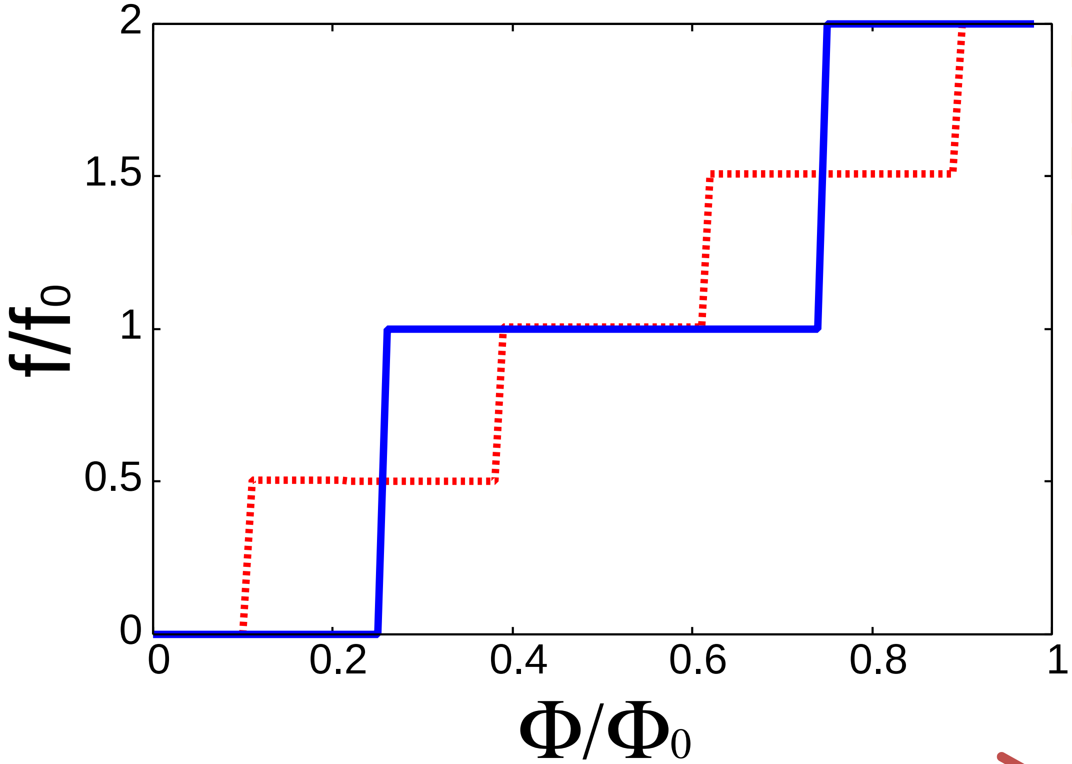


Balanced gas (BCS state)



Half quantum vortex → Half period of Little-Parks oscillation

Half quantized mass current



Blue line: balanced gas

Red line : imbalanced gas

Rotation

The mass current is half quantized in the A-FFLO superfluid state

Summary

Toroidal trap + Feshbach resonance

↓

We can produce and observe the Angular-FFLO state!!

↓ Rotation

Half quantum vortex state

Study in future: (A) Trap geometry

(B) Optical lattice

(C) Dipole interaction

Summary

Toroidal trap + Feshbach resonance

↓

We can produce and observe the Angular-FFLO state!!

↓ Rotation

Half quantum vortex state

Thank you very much for your attentions